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STATUS REPORT ON TRAPPED ELECTRONS FROM THE STARFISH HIGH ALTITUDE NUCLEAR TEST

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I. Character of the Artificial Radiation Belt

Information relative to the injection of electrons into the earth's magnetic field, as a result of the STARFISH high-altitude test of July 9, 1962, is available from the degradation experienced by solar cells of satellite power supplies, from the counting rate of particle detectors mounted in satellites and, potentially, from observations of radio noise. Only the data from particle detectors can be expected to give a detailed picture of the spatial distribution of these electrons, but the other observations may serve to provide an integrated check of the inferred distribution. The data from the various particle detectors have been interpreted on the assumption of an energy distribution which, at all points, is that representative of beta rays from fission products, and no evidence has been obtained which would indicate that this assumption is not substantially correct.

The effects with which we are concerned here are not the lower altitude phenomena, such as artificial auroras or interference with radio communication, which are very transient in nature. We are instead concerned with phenomena related to the Van Allen belts, which occur at higher altitudes.

The earth's magnetic field can be depicted by a series of magnetic lines of force which arch from the vicinity of the north to that of the south magnetic pole. Electrically-charged particles introduced at high altitudes where there is little interference by the atmosphere will be bent by the magnetic field and circulate about a line of force. Any initial north-south motion will result in a rapid oscillation of the particle along a helical trajectory which extends between conjugate mirror points where the magnetic field is sufficiently high to effect a reflection of the particle. Because of the arched shape of the magnetic lines, the extremes of the north-south motion will be in regions of higher atmospheric density than in the middle, and particles whose mirror points fall at sufficiently low altitude will be rapidly absorbed. A slow precessional motion in the east-west direction is superposed on the rapid north-south oscillations because of the inhomogeneity of the earth's magnetic field. Because of the eccentric nature of the field, a given set of particles will drop to considerably lower altitudes as they pass over the South Atlantic Ocean and will be subject to maximum atmospheric absorption in that region.

The natural Van Allen belts consist of charged particles (protons and electrons) which are held in regions external to the earth by the earth's magnetic field. Although it had been conjectured prior to the STARFISH test that distortion of the magnetic field by a high-altitude test might result in a loss of some particles from the inner natural belt, the predominant effect was recognized to be the injection into the earth's field of beta particles resulting from the decay of charged or uncharged fission products. In this way a new electron belt is formed, superimposed upon and extending somewhat below the natural Van Allen belts, whose character and modification in time is of considerable interest and whose behavior should add to our understanding of the natural radiation belts.

The first picture of the artificial radiation belt was obtained from the Injun satellite. A paper by O'Brien, Laughlin and Van Allen has been published on this subject. Important data was also provided by the ARIEL, TRAAC and TELSTAR satellites.

The data which at present are available do not yet give a completely consistent picture as to the distribution and persistence of the injected electrons from STARFISH, since measurements from different satellites are in disagreement by a factor of 2 and occasionally 4, as judged from instances where the observations overlap. The data from TELSTAR, which to date has provided the most extensive coverage of the artificial electron belt, show internal fluctuations which in some cases are as large as a factor of 10; however, these fluctuations have been at great distances from the earth where the artificial belt and natural belt are merging. In this connection there is also a matter of questionable performance of tracking stations at Woomera and Johannesburg in the Southern Hemisphere. The numbers indicated by the data imply the injection of electrons at higher altitudes and in much greater abundance than was anticipated.

From the data available by August 28 from the particle detectors, contour maps of radiation flux (omnidirectional intensity) in B,L-space[x] were constructed. The data were considerably more abundant at the lower altitudes, and the extension of the contours to large radial distances consequently is least certain. The map which refers to the first week following the STARFISH test is shown in Fig. 1, and the corresponding plot in geomagnetic R,λ coordinates is shown in Fig. 2. The plot in Fig. 2 does not, however, represent completely the detailed distribution about the earth, since local field irregularities and the eccentricity of the geomagnetic field are removed in this form of presentation. It is seen generally that the maximum intensity appears to occur at a mean altitude of about 4000 km, and that the contour for which the electron flux is 10^9 $cm^{-2}sec^{-1}$ is approximately 5000 km thick and extends 6000 km in the north-south direction. This peak flux is about ten times the maximum ever observed in the outer natural Van Allen belt and a factor of 100 above the usual maximum conditions there, but the intensities in the natural belt are even less well known than are the characteristics of the new belt of artificially-injected electrons.

From an intercomparison of the observational data and an appreciation of uncertainties in detector calibration, it is estimated that the intensities cited may be low by a factor of 2 or may be high by a factor of 2 to 4. From a volume integration of the intensities

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[x]In a dipole field, L characterizes the radial distance to a line of force measured in the equatorial plane (in units of earth radii), and B denotes the strength of the magnetic field at an observation point on this line (in gauss).

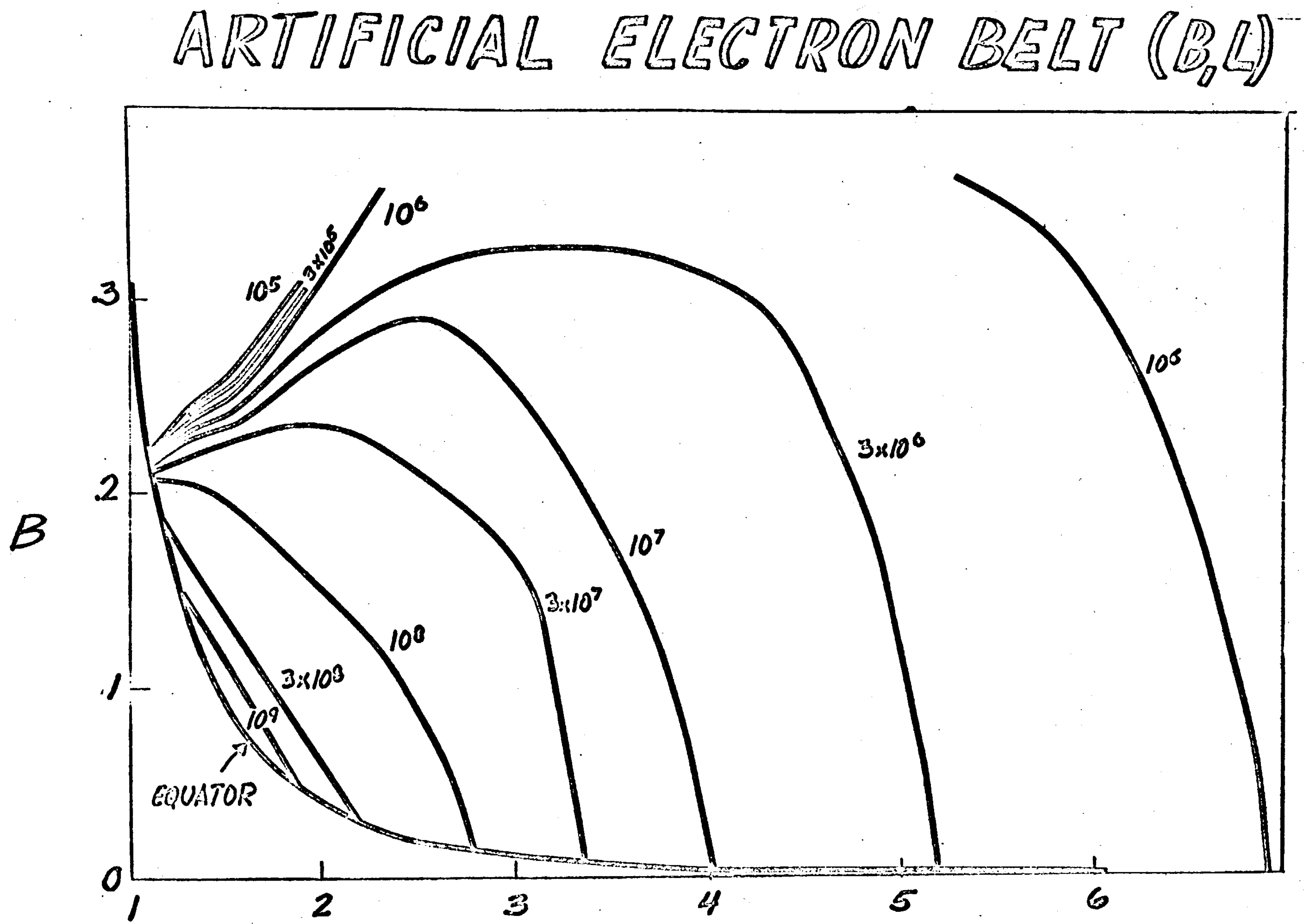

FIG. 1. Contours of Omnidirectional flux in electrons/cm^2 - sec during first week, plotted in B,L space. (B in gauss L in earth radii)

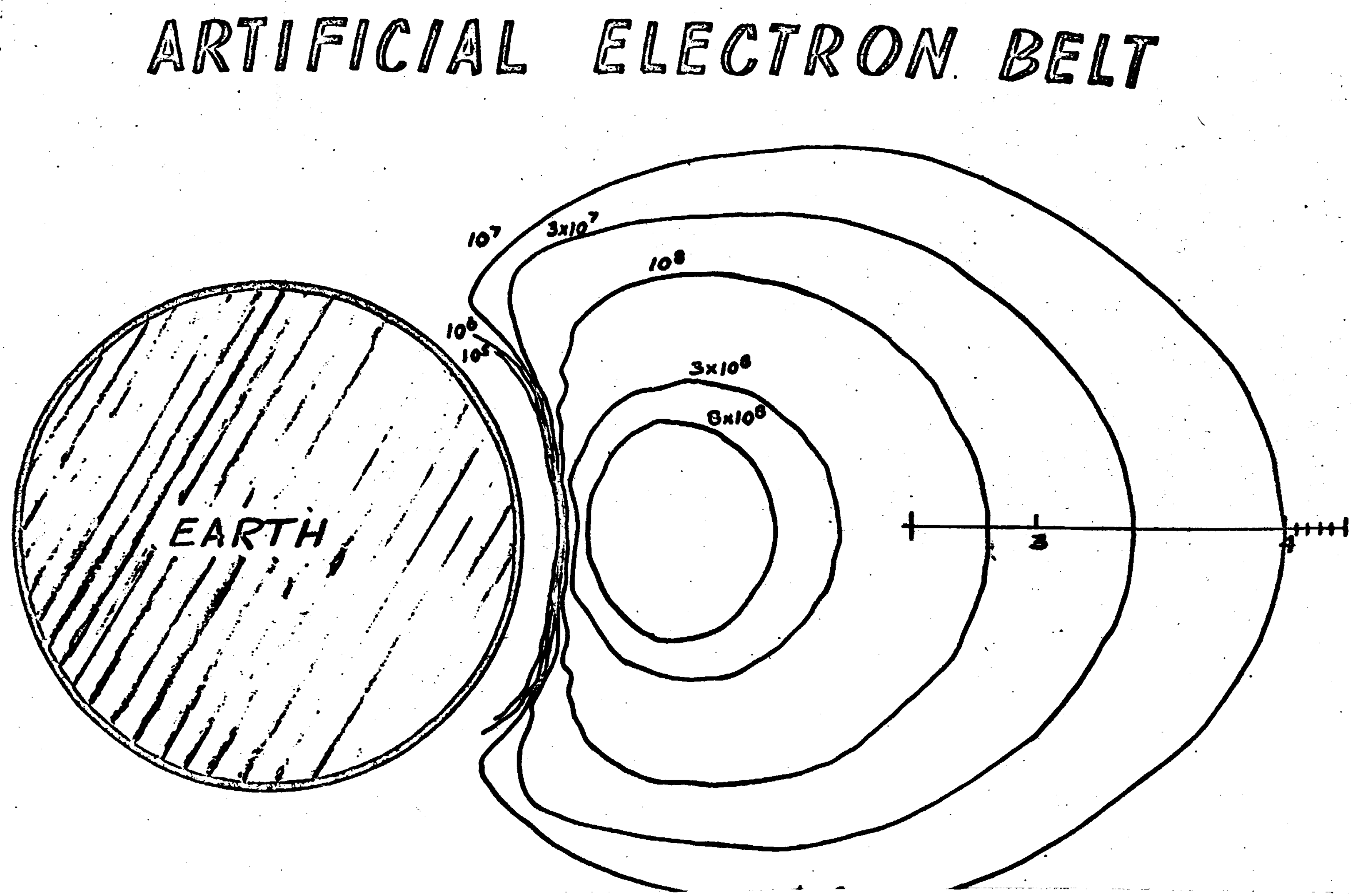

FIG. 2. Contours of omnidirectional flux in electron/cm^2 - sec, during first week, plotted in R,λ coordinates adjacent to the earth.

portrayed in Fig. 2 the total number of trapped electrons is computed to be 2×10^{26} within the contours of Fig. 2. This result, of course, is subject to the uncertainties mentioned above in regard to the quantitative evaluation of the data -- in addition to suggesting a high capture efficiency, however, it appears from these results that the preponderance of the captured electrons indeed must be those arising from fission-product decay and that only a small fraction could be attributed to the decay of neutrons produced by the nuclear test.

II. Persistence of the Artificial Electron Belt

Aside from data which indicate a noticeable decrease of intensity during the first day following the STARFISH test, definitive information is lacking concerning the decay of the trapped electrons. In constructing from TELSTAR data contours similar to those of Fig. 1, it seemed that by the second and third weeks a marked change occurred in the location of the lower-intensity contours which appear at high B,L values. A more complete perusal of the TELSTAR data has not, however, shown such a marked decrease of intensity generally. Results recently obtained (August 31) from the INJUN project, at relatively lower altitudes, suggest a decrease of intensity in some regions by a factor of 2 to 4 in 8 weeks. Observations of radio noise, which is produced by high-energy electrons at a low altitude in the belt, have shown a decay of about 10 percent per week.

It is believed that the chief mechanism for electron loss is atmospheric scattering, whereby the pitch angles of individual electron trajectories may be changed and so lead to deeper penetration into the atmosphere. A slow degradation of energy also will occur due to the electromagnetic radiation which results from the centripetal acceleration of the electrons in the earth's field ("synchrotron radiation"), and some loss may also be expected to result from severe magnetic storms.

With respect to the scattering process, the electrons which remain for the longest time are those confined close to the equator at high altitudes, where the atmospheric density is very small. Such electrons will be scattered only infrequently as they move along the field lines, and their lifetime thus will be long. The equatorial region at high altitude accordingly will feed electrons to regions of higher latitude at a low rate and the high-altitude population will decay only slowly. The population at low equatorial altitudes will decay more rapidly, since the density is significantly greater, and the electrons become lost in the relatively dense regions at low altitudes over the South Atlantic Ocean where the field shell dips lowest. This region (at 35° S., 35° W.) furnishes most of the radiation exposure to low-altitude space missions.

The atmospheric densities which are required for a computation of electron lifetime are not well-known at the relevant altitudes of about 1100 km over the South Atlantic. The atmospheric density in fact is believed to vary by a factor of about 200 over the five-year interval between a maximum of solar activity and the following solar minimum. The densities vary, moreover, by a factor of 10 from day to night, and the abundance of nitrogen relative to hydrogen and helium also varies markedly throughout the atmosphere. The available atmospheric data were obtained during a period near a solar maximum, so that electron lifetimes estimated for that epoch should be uncertain by no more than a factor of 10. It accordingly appears most reliable to present (see Appendix I) the lifetimes computed for a period of solar maximum and then to give the estimates for the present state of solar activity.

The 2-Mev electrons which mirror near the equator, at 1100 km equatorial altitude, are calculated to have a lifetime of about 15 days during a solar maximum ($N = 1.3 \times 10^6$ oxygen atoms per cm^3). (See Appendix I, Table I). At the present stage of solar activity, however, the corresponding lifetime may be 150 days. Such electrons are expected to be dumped into low, and hence dense, regions of the atmosphere over the South Atlantic; at the northern end of this hot spot the radiation thus should decay at present (at least to one-third of its initial value) with a half-life of about 100 days. Electrons which move along field lines further south have higher altitudes at the equator (about 1400 km), and their decay at present may be expected to have a half-life of about three years. Since experimental corroboration, although not lacking, is spotty, these estimates readily could be in error by a factor of 5.

The greater number of the stored electrons will have a lifetime comparable with that characteristic of the natural Van Allen belt. These lifetimes are believed to be many years, and a half-life of 20 years is considered representative for electrons at an equatorial altitude of 2600 km. As is illustrated by results presented in Appendix II, moreover, a more significant degradation of electron energy by the mechanism of synchrotron radiation would occur only in times which are considerably greater than the lifetimes due to atmospheric scattering.

III. Effects on the Unmanned Satellite Program

The radiation doses encountered by present satellites in moving through the artificial electron belt, and those expected for possible future satellite missions, were integrated by digital computation on the basis of the electron distribution portrayed in Fig. 1. The result of 2.8×10^{12} electrons cm^{-2} day^{-1} for ARIEL and 4.5×10^{12} electrons cm^{-2} day^{-1} for TRAAC - TRANSIT 4B agrees well with the rapid deterioration of the solar-cell power supplies for these vehicles in 3 to 4 days and 24-36 days, respectively. The power systems for these satellites were designed with only natural radiation environment in mind and effectively no shielding, in the interest of reducing size and weight, so that a 25-30 percent reduction of output would markedly or completely impair the system performance and result in a termination of useful transmissions from the vehicles before the end of the period for which the power systems were designed. The choice of a different type of solar cell (n-on-p silicon, protected by 0.030 inch of sapphire) and the more conservative design of the power supply system permits TELSTAR to accomplish its mission in spite of increased radiation intensities. Future NASA missions are being reviewed in light of the present information concerning the new belt, and it is anticipated that a substantial number of the missions will be affected. The very satisfactory performance exhibited by TELSTAR in the heart of the radiation belt from the STARFISH test shows, however, that it indeed is possible to design solar-cell power supplies to have a satisfactory life in such an environment.

IV. Influence on the Current Manned Space Flight Program

Mercury flights at altitudes (160 - 265 km) and durations which so far have been planned, are not endangered by the stored electrons. From the observed distribution of electron flux, as presented in Fig. 2, one may calculate readily the external radiation intensity during a planned satellite mission. The total radiation exposure external to the capsule during a six-orbit Mercury mission on a MA-7 trajectory thus would be about 500 r on the basis of the electron flux pattern shown in Figure 2. It is further estimated that an external dose of 500 r would lead to an electron dose inside the vehicle of about 8 r to the astronaut's skin. This exposure is well below the mission limit previously established by NASA for the Manned Flight Program. It is noted that this type of exposure does not constitute a whole-body irradiation, in contrast to the more severe situation encountered with gamma-rays or higher-energy protons.

The Vostok cosmonauts received very small radiation doses in their recent mission, in view of the lower altitude of their orbit and their presumed heavier shielding. The cosmonaut exposures of 0.050 rad and 0.036 rad published by the Soviets for these flights can be accounted for by cosmic-ray exposure and consitute an entirely acceptable level for whole-body gamma irradiation in such a mission.

V. Effect on Non-Satellite Science

While many more electrons were trapped as a result of the STARFISH test than had been anticipated, the observed increase of radio noise was about as expected and now is nowhere more than a factor of two above the cosmic noise prior to the test. The observable radio-noise is confined to low magnetic latitudes, and its magnitude is sensitive only to that fraction of electrons which have high energy and are situated at low altitudes. The radiation is polarized, although rotated by traversal of the ionosphere, and its magnitude is particularly sensitive to the mirror-point distribution of high-energy electrons in regions of strong magnetic field when observed with a narrow beam antenna.

The observations have been made at various locations for frequencies between 18 and 120 megacycles per second. The noise is decreasing with time, at present at a rate of about 10 percent per week. For the reasons noted above, however, the decay of the radio-noise, while gratifying, does not imply that most of the electrons are disappearing at a similar rate. There is no other known effect of the injected electrons which is observable on the earth. The radio-noise will remain detectable at the lower latitudes for a long time if special techniques are employed, but it does not constitute a significant problem to radio astronomy.

VI. Acknowledgments

It should be mentioned that helpful and complete cooperation has been obtained from the various scientific groups who have been in a position to provide the U. S. Government with information relevant to the electron belt. In most instances the data have not yet been thoroughly analyzed by these groups.

Analysis of the preliminary information as it was received and computation of the doses to be expected on various satellite missions was performed by Dr. W. Hess of the NASA Goddard Space Flight Center.

APPENDIX I

[Based on an analysis by J. A. Welch]

RESERVOIR LIFETIMES

An upper limit for the mean lifetime of the electrons trapped in any L shell is given by the mean time required for a particle originally mirroring on the equator to be lost by atmospheric scattering. Unfortunately, even this limit is uncertain because it depends directly on atmospheric densities and compositions which are uncertain to factors of 3 to 5.

Any mirror-point distribution will adjust itself in about this time to a fundamental mode having a maximum mirror point density at the equator. If the distribution originally were peaked well off the equator, then most of the total population would be lost in this same interval. If the distribution were originally near the fundamental mode, then a smaller fraction ($\approx 2/3$) would be lost. In either case the population will decrease exponentially, with the reservoir lifetime, after attaining the fundamental mode.

The "1/t" decay appearing in the ARGUS literature referred to populations far off the equator and to times less than the reservoir lifetime. That is, it applied during the readjustment from a fairly constant mirror-point distribution to the fundamental mode. The highest modes decay most rapidly. At time t, the population changes are due to those electrons in a mode whose mode lifetime is just about equal to t. Higher modes have already decayed and lower modes have yet to change. The over-all result is a 1/t - decay near the ends of the lines.

We employ an expression for multiple Coulomb scattering which is based on a study by Moliere that has been verified experimentally for 2-Mev electrons. This analysis gives for relativistic electrons in an oxygen atmosphere of N atoms/cm^3

$$\frac{d}{dt}(\theta^2) = \frac{1.2 + 0.2 \ln \qquad\qquad}{\gamma^2} \; N\times 10^{-11} \text{ sec}^{-1}.$$

Helium is less effective by about a factor of ten.

The angular deflection necessary for loss in the normal mode is that necessary to move a mirror point from the equator to a position where the atmospheric density is an e-folding higher. If we denote this angle by a, the lifetime is taken to be

$$t = 2\alpha^2 / \frac{d}{dt}(\theta^2).$$

The factor of two accounts for those scatters that do not change the pitch angle.

In applying the foregoing result, one of the courses must use the atmospheric density averaged over longitude. This can be well approximated as one-tenth of the density at the magnetic anomaly. The atmospheric model and the derived reservoir lifetimes are given in Table I. Estimates of atmospheric densities at sunspot minimum (which we are now approaching) are much lower than the values in Table I. The lifetimes accordingly could be longer, as is suggested by the last column in Table I.

TABLE I. SCATTERING LIFETIME FOR ELECTRONS WITH $\gamma = 5$

L (Earth Radii)	B at Equator (gauss)	Equatorial Altitude (km)	Density during solar maximum Oxygen (cm^{-3})	Helium (cm^{-3})	Reservoir Lifetime (days) Solar Max.	Estimate for 1962[a)]
1.15	0.204	380	2×10^9	9×10^6	0.02	0.2
1.20	0.180	700	3×10^7	3×10^6	0.9	9
1.25	0.160	1100	1.3×10^6	2×10^6	15	150
1.30	0.142	1400	2×10^5	1.3×10^6	140	1500[b)]
1.35	0.127	1800	1×10^4	6×10^5	1000	10^4 [b)]
1.40	0.113	2200	3×10^2	3×10^5	3000	3×10^4 [b)]
1.45 [c)]	0.102	2600	10	1.5×10^5	8000	10^5 [b)]

a) A reasonable ratio of the present air density to that at the solar maximum is 1/5 - 1/50; we take here a ratio of 1/10.

b) Lifetimes longer than 1500 days should be discarded, since this interval would extend into the following solar maximum. In such cases, lifetimes which are three times those for solar maxima should be employed.

c) For values of L greater than 1.45, the mechanism of energy loss dominates. This is because of the lower average Z of the atmosphere at such high altitudes and the larger angle which is required for a significant scattering loss.

APPENDIX II

ENERGY LOSS BY SYNCHROTRON RADIATION

/L. Jackson Laslett/

As has been noted, the electron loss by atmospheric scattering is least for those electrons which remain close to the equator at high altitude. The energy loss by centripetal acceleration (synchrotron radiation) will also be comparatively low in this region, since B is low there, but it is of interest to determine the time required for a degradation of electron energy by the mechanism of synchrontron radiation.

The radiated power may be written[1/]

[1/] W. K. H. Panofsky and M. Phillips, Classical Electricity and Magnetism (Addison-Wesley Publishing Co., Inc., Reading, Mass., 1962), Ed. 2. (20-39), p. 366

$$P = \frac{2}{3}\frac{r_o c}{\rho_o^2}(\beta\gamma)^2 \; m_o c^2$$

$$= \frac{2}{3}\frac{r_o c}{\rho_o^2}(\gamma^2-1)\, m_o c^2 ,$$

where

$$r_o = \frac{e^2}{m_o c^2} = 2.82\text{x}10^{-13} \text{ cm}$$

and $$p_o = \frac{m_o c^2}{eB} = \frac{1703}{B_{gauss}} \text{ cm.}$$

Thus $$-\frac{d\gamma}{\gamma^2-1} = \frac{2}{3}\frac{r_o c}{\rho_o^2}\, dt,$$

and $$T = \frac{3}{2}\frac{\rho_o^2}{r_o c}\left[\text{ctnh}^{-1}\gamma_f - \text{ctnh}^{-1}\gamma_i\right]$$

$$= \frac{3}{4}\frac{\rho_o^2}{r_o c} \quad \ln\left(\frac{\gamma_f + 1}{\gamma_f - 1} \cdot \frac{\gamma_i - 1}{\gamma_i + 1}\right)$$

$$= \frac{5.924\times10^8}{B^2_{gauss}} \log_{10} \left(\frac{\gamma_f + 1}{\gamma_f - 1} \cdot \frac{\gamma_i - 1}{\gamma_i + 1}\right) \quad \text{seconds}$$

$$= \frac{18.77}{B^2_{gauss}} \log_{10} \left(\frac{\gamma_f + 1}{\gamma_f - 1} \cdot \frac{\gamma_i - 1}{\gamma_i + 1}\right) \text{ years.}$$

We tabulate below the time required for radiation to effect a reduction of the kinetic energy to 0.5 Mev ($\gamma_f = 1.978$).

TABLE II

TIME FOR KINETIC ENERGY TO DROP TO 0.5 Mev BY RADIATION, years

E_i (kinetic) Mev	γ_i	B gauss 0.15	0.20	0.25	0.30
1.0	2.957	148.3	83.5	53.4	37.1
1.5	3.935	215.	121.	77.2	53.8
2.0	4.914	254.	143.	91.5	63.5
2.5	5.893	279.	157.	101.	69.8
3.0	6.871	297.	167.	107.	74.3